



CFD Modeling of Plume Induced Environments for Space Shuttle Liftoff Debris Transport Analysis

Fluid Dynamics Analysis Branch (ER42)

NASA Marshall Space Flight Center

Peter Liever (CFDRC/ESTS/ER42)

Jerry Radke (CFDRC/ESTS/ER42)

Louise Strutzenberg (ER42)

Jeff West (ER42)

2nd Workshop on Lunar and Martian Plume Effects and Mitigation

NASA KSC

January 20-21, 2011



Outline



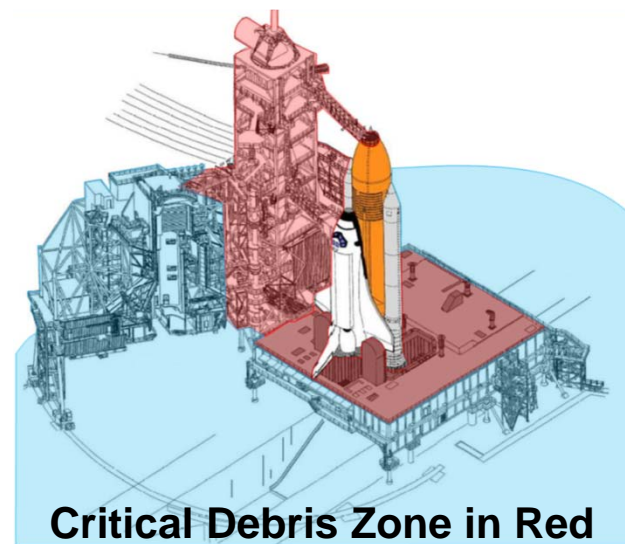
- Shuttle Liftoff Debris Transport Analysis Process
- Application of CFD Analysis to Understand Liftoff Flow Events and Assess Resulting Debris Risk
- Overview Of Liftoff CFD Analysis Tool Capabilities
- Shuttle Launch Pad Liftoff Computational Model
- Samples Of Quasi-Steady Shuttle Liftoff Flowfield Simulations Applied in Debris Transport Analysis
- Importance Of Recent Advances in Vehicle Motion And Unsteady Flow Effects Modeling



Space Shuttle Liftoff Debris Definition



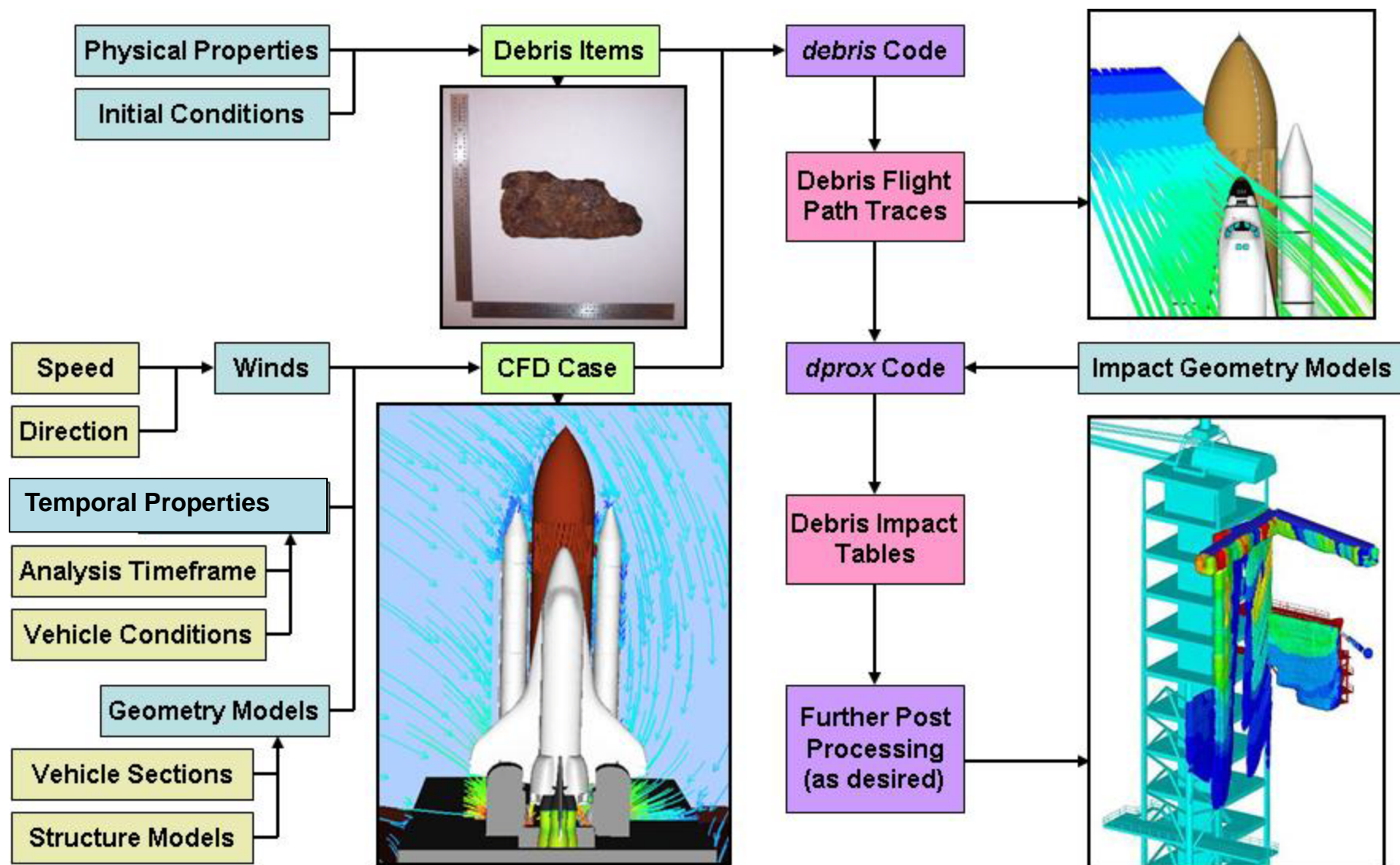
- Liftoff Debris Is Any Hazardous Mass Transporting Inside The Critical Debris Zone From Tanking Through Vehicle Tower Clear
- Debris Transport Analysis (DTA) Includes
 - Liberation
 - Transport
 - Damage Tolerance
- CFD Modeling Of Plume Induced Environments Is A Key Element Of DTA For The Liftoff Timeframe



Critical Debris Zone in Red



Debris Transport Analysis Process

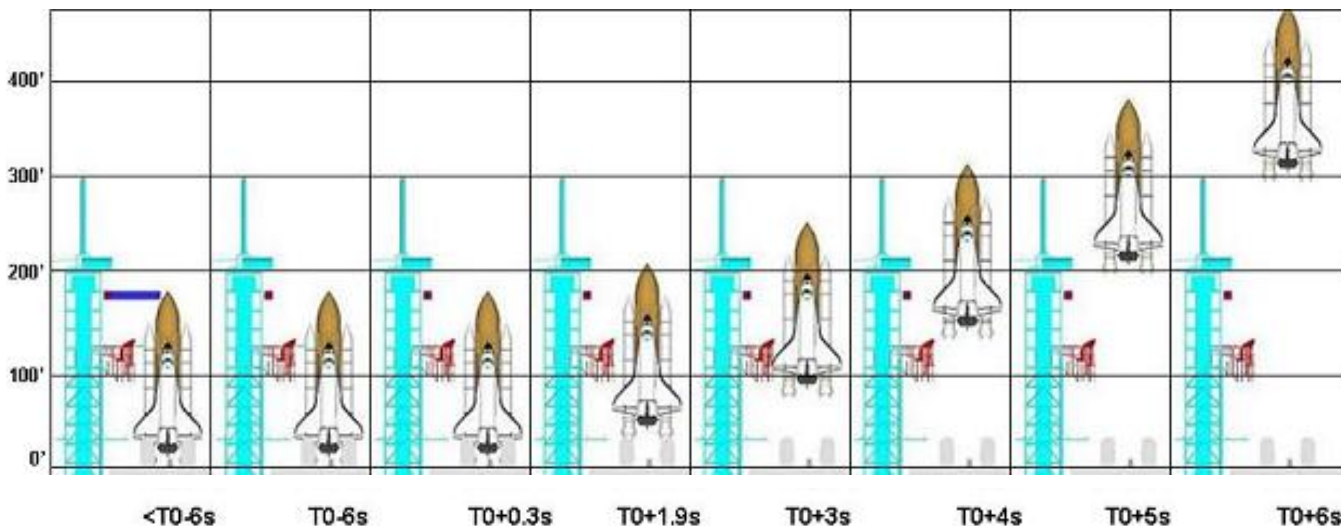




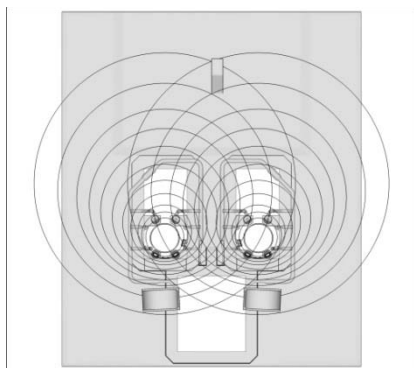
Temporal and Spatial Framework of Analyses



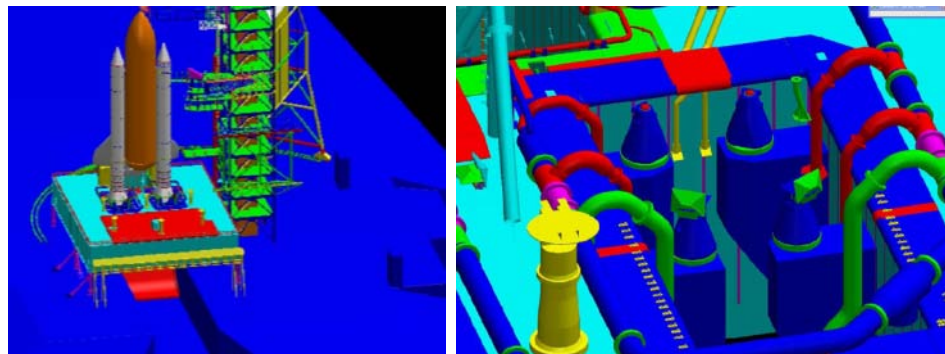
Key Vehicle Positions with Time During Liftoff



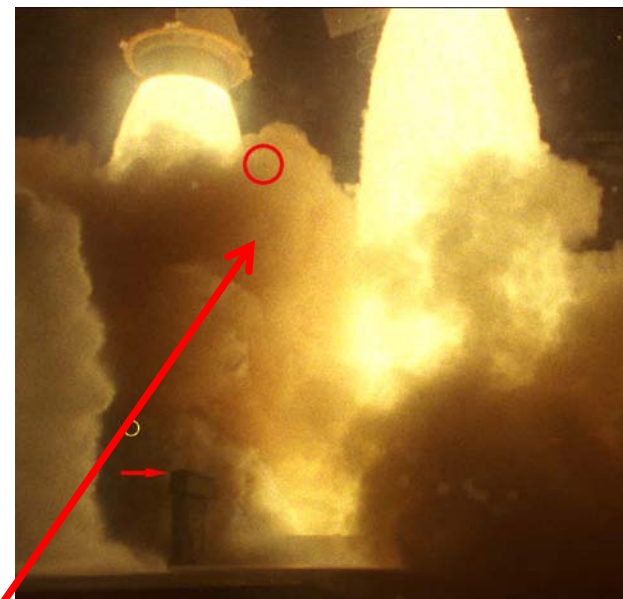
Plume Foot Print on MLP
Deck changes with time



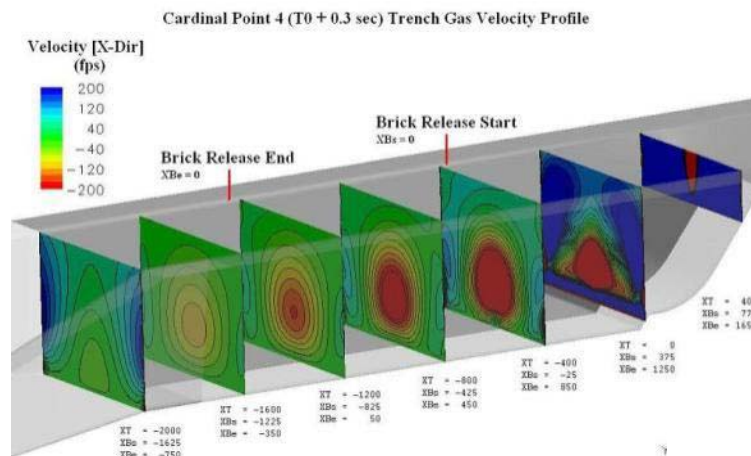
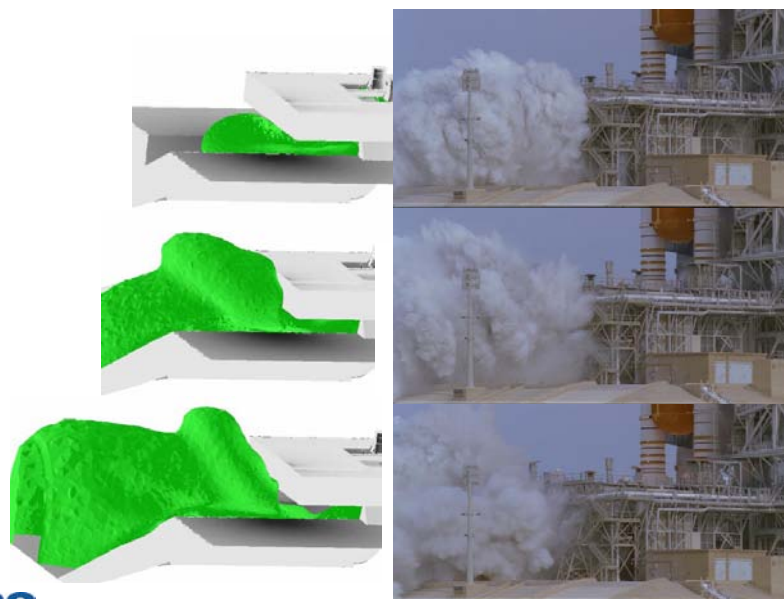
CAD Models Detail Position & Geometry of Major Structures



- Simulate Interaction of Wind and Plumes with the Vehicle and Launch Pad Structure
 - Steady State Models
 - Transient Models (with body motion)
- Identify Flow Features Driving Debris Transport
 - Wind & Gravity Features
 - Plume Entrainment & Plume Driven Features
- Model Validations Via Comparison With Actual Launch Data Imagery And Instrumentation Records
 - Drives Modeling Improvements To Capture Event Physics



Upward Moving Flow

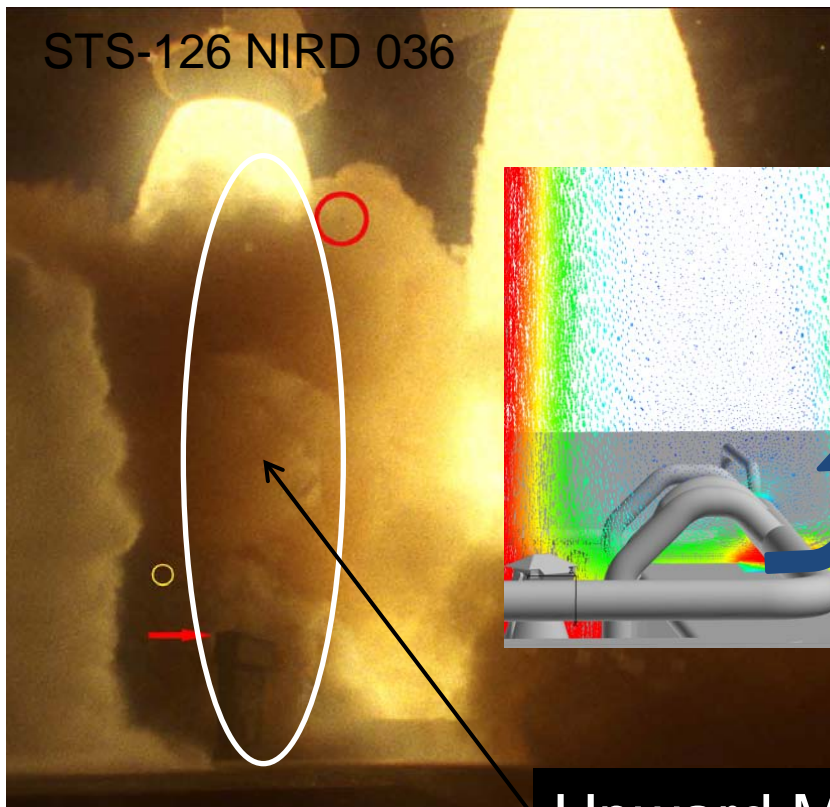




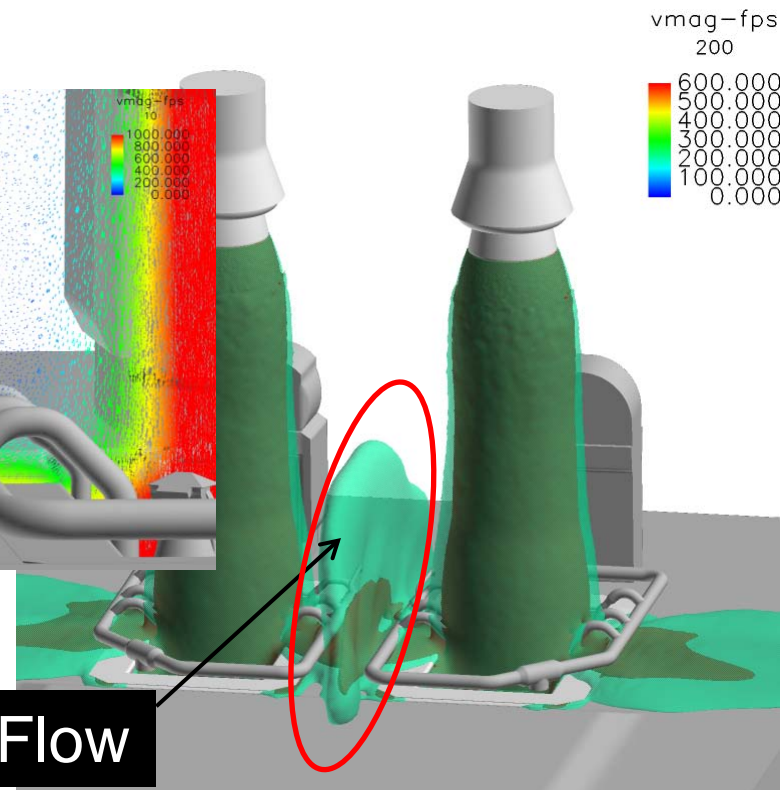
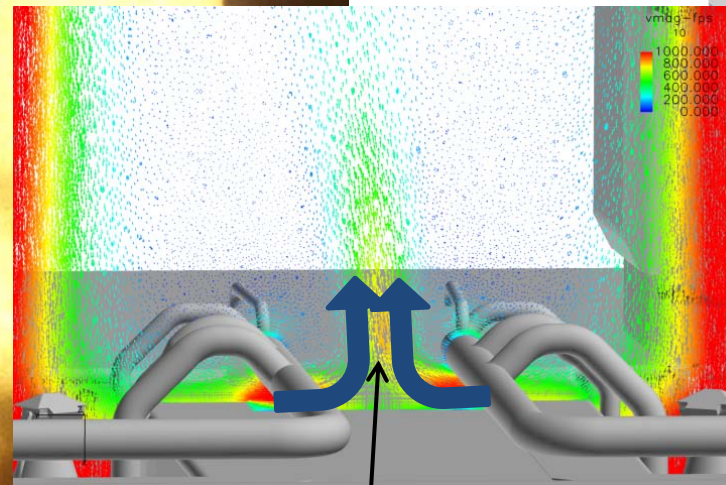
Example of Debris Transport Explanation with CFD



- An upward moving debris item (NIRD-126-036) was observed on STS-126 and is shown in the figure to the left at MET ~ 3 sec.
- CFD confirms the two SRB plumes impinge on the MLP deck, collide near the plane of symmetry between the SRB ducts and produce an upward fountain-like flow feature
- LODTA analysis then used to track debris through CFD flow field and identify risk and damage potential.



CFD Solution at T0+3.0 sec



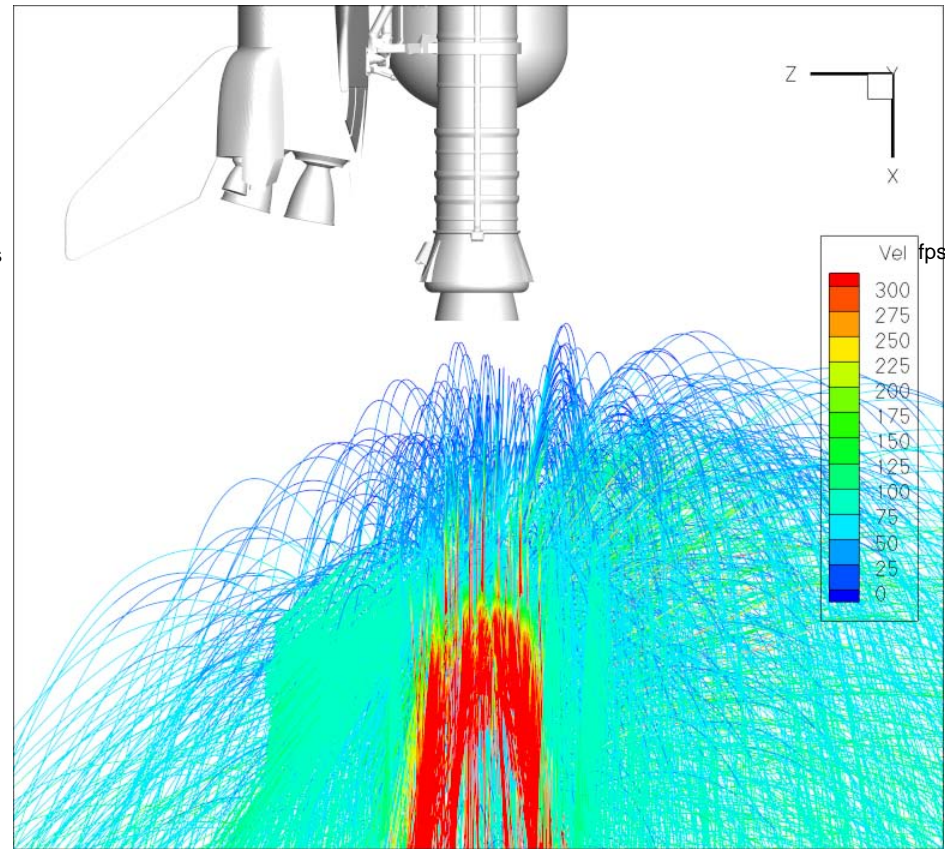
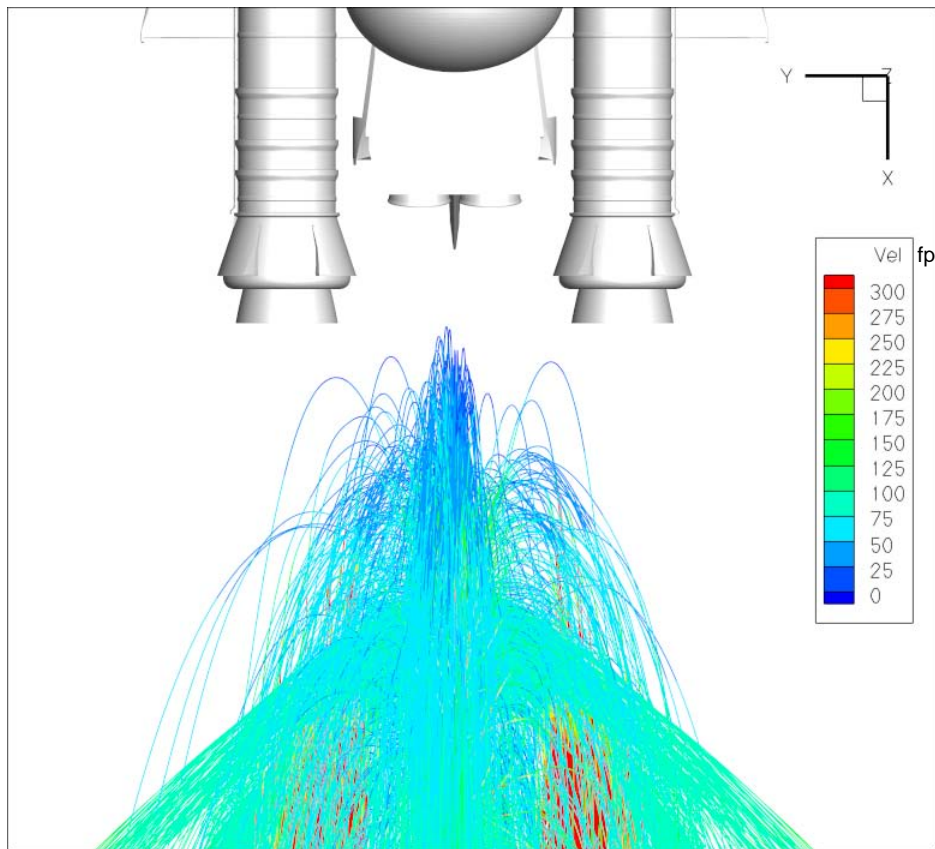
Upward Moving Flow



Example of Debris Transport Explanation with CFD



- LODTA analysis with permutations in debris properties and initial release conditions provides bounding analysis of possible debris trajectories, impact locations and impact kinetics
- Analysis shown indicates debris most likely does not reach sensitive Orbiter Components



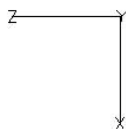
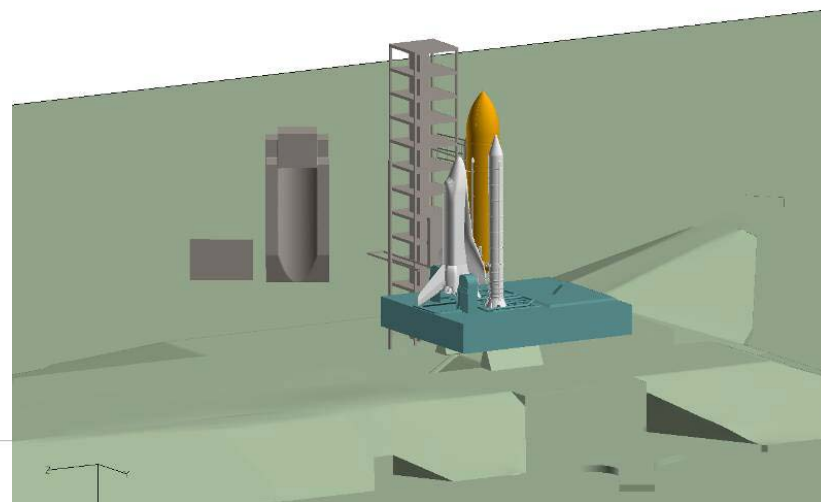


Loci/Chem Flow Solver Information

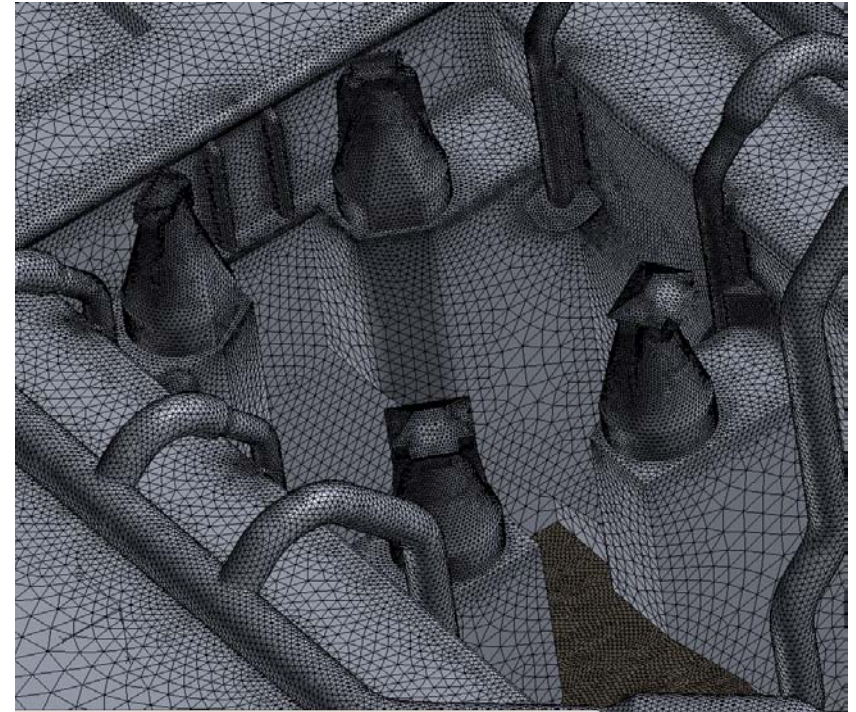
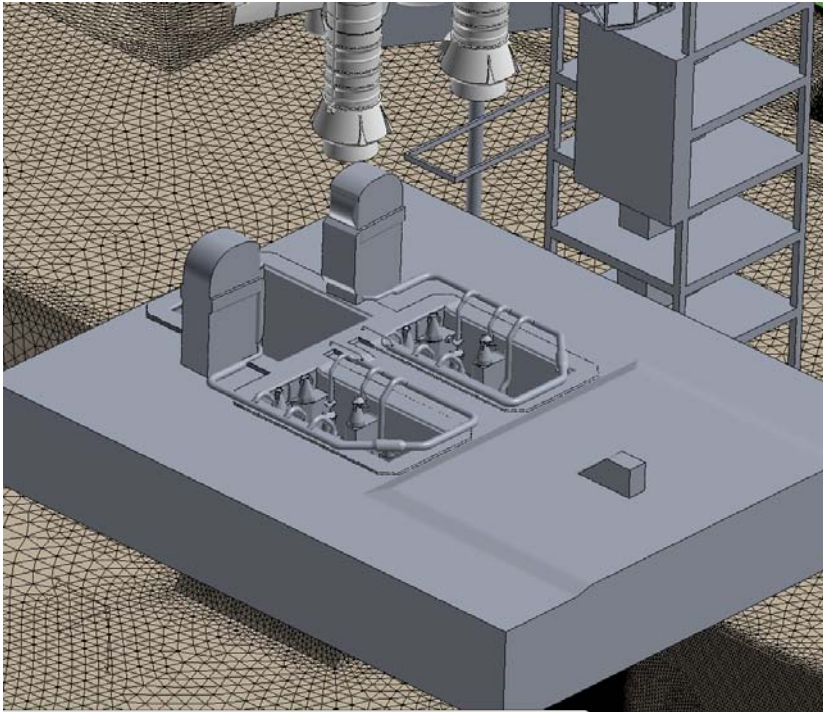


- The Loci Framework (Miss. State University)
 - C++ Libraries To Assist Code Development And Enable Massive Parallelism
 - 504M Cells On 3,000 CPU Cores (NASA AMES Pleiades Cluster)
 - Developed With Funding From NASA Over The Last 13 Years
- The Loci/Chem CFD program (Miss. State University)
 - Develop With Funding From NASA Over The Last 13 Years
 - Significant Recent Investment From Both Army And Air Force
 - Used As The General Purpose CFD Program At NASA/MSFC For:
 - Combustion Devices CFD (Reacting Cryogenic Injector And Nozzle Flows)
 - Launch Pad Environments (Plume Impingement, IOP, Plume Splash, Acoustics, Mitigation Systems Simulation)
 - Propellant Delivery Systems (Valves, Ducts And Turbines)
 - Verified Using Formal Method Of Manufactured Solution Methods
 - Validated Over A Wide Range Of Applications By NASA/MSFC Personnel
 - Plume Structure, Impingement, Entrainment
 - Significant Validation In Both Steady And Unsteady Modes
 - Density-based Algorithm In An Unstructured Mesh Framework
 - Second Order In Time And Space
 - RANS And Hybrid RANS/LES Turbulence Models
 - Unstructured Overset Capability (Prescribed Motion And 6-DOF)

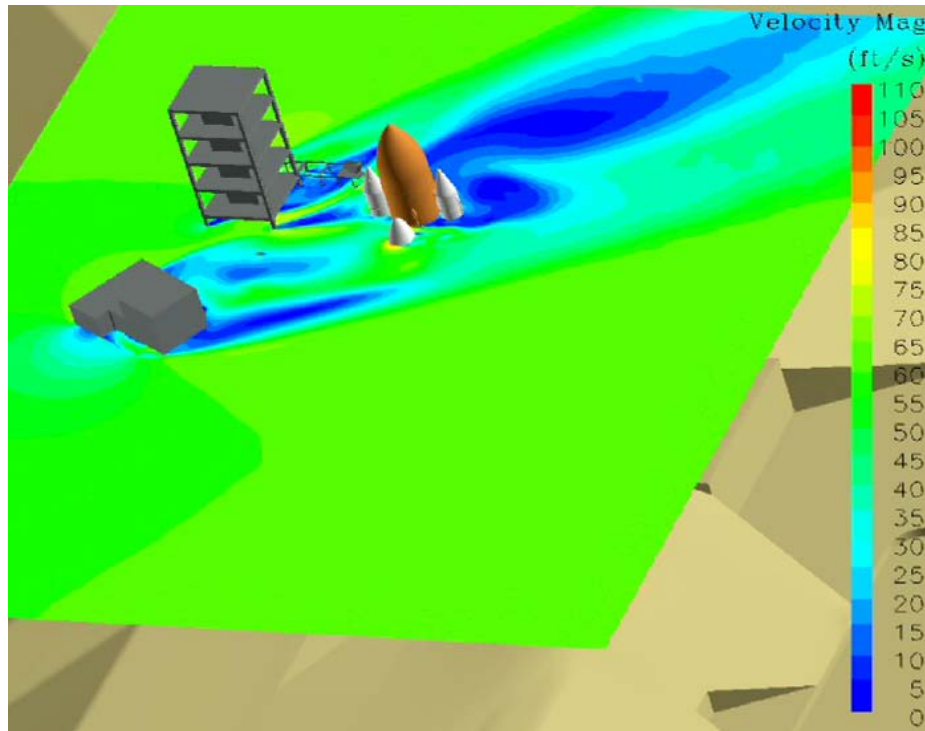
- Liftoff CFD Model resolves Important Global and Local Features
- Large Domain with Launch Pad Hill with Crawler Ramp and Sloped Side Wall Details to Accurately Capture Wind Boundary Layer Accelerating over Hill
- Key Service Structure Components Affecting Wind Blockage
- MLP details affecting plume flow



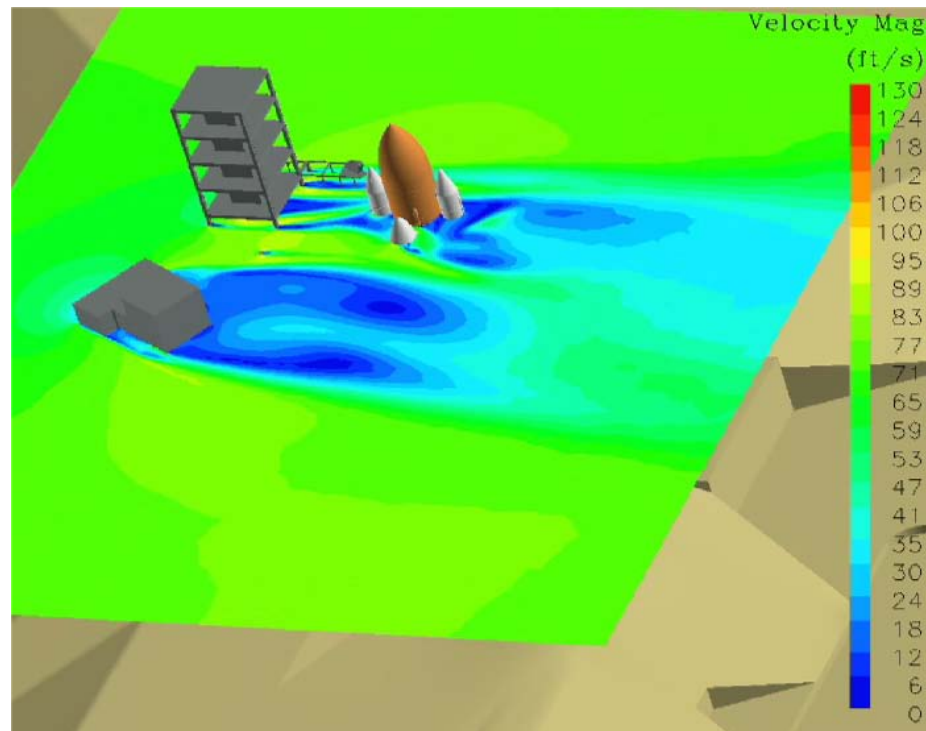
- MLP SRB Exhaust Port Details Affecting Plume Obstruction And/Or Upward Deflection
 - Pipes, Haunches, Hold Down Post Shoes, Blast Shields, ...



- Steady State CFD Analysis of Wind Effects
- Wind Flow Field At The FSS 215' Level.
- Notable Wakes Created By Facility Structures Affect Debris Transport.

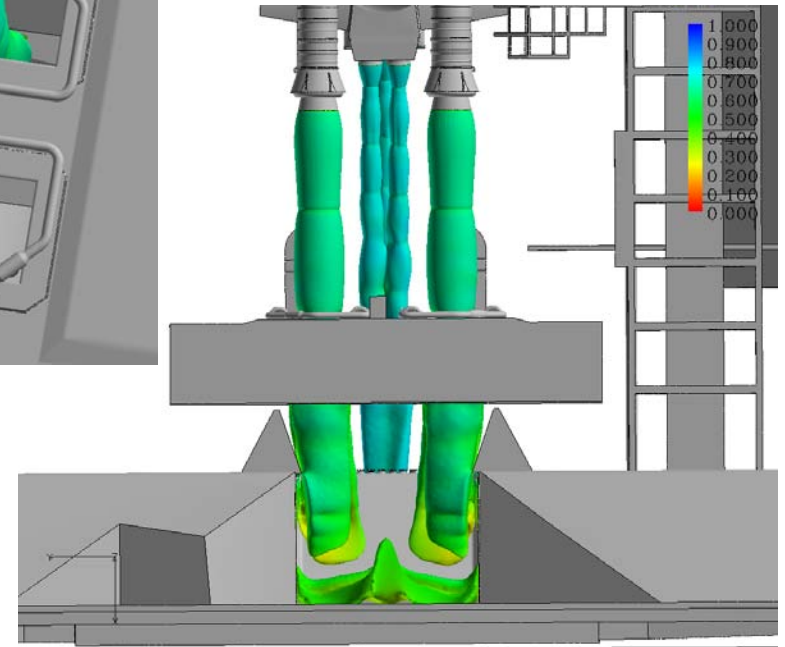
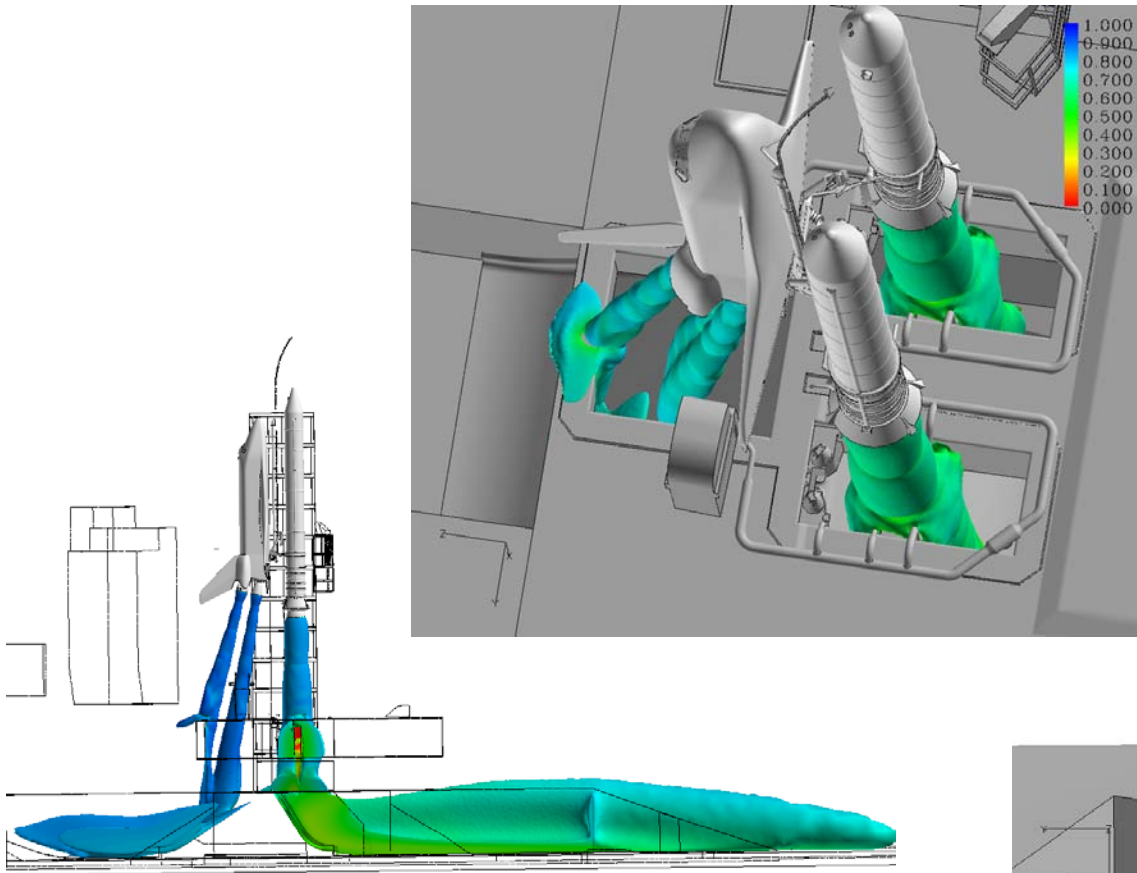


Wind 27 kts from 225 deg

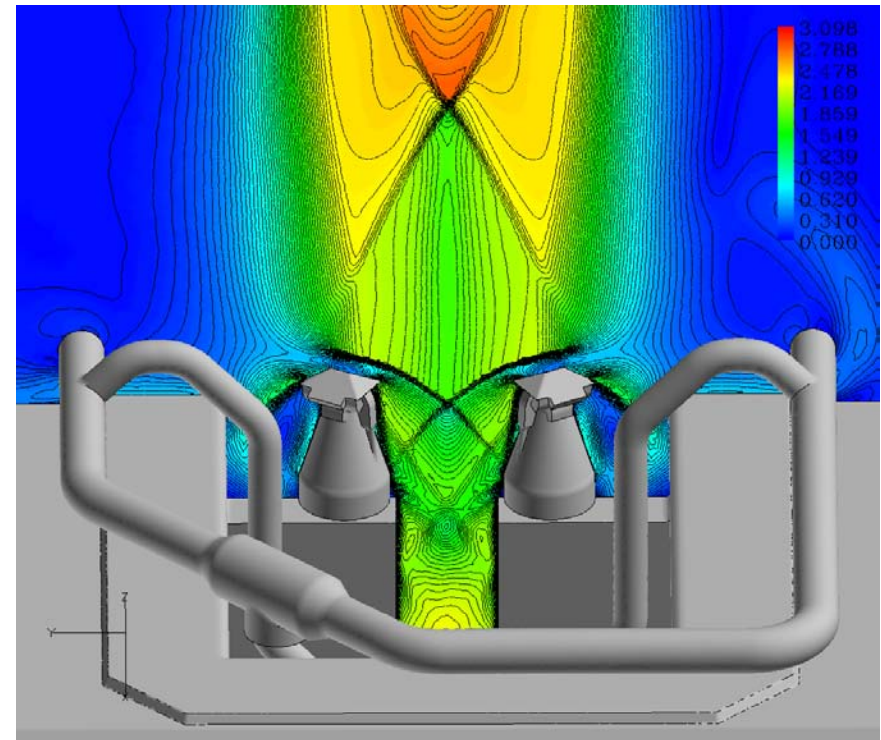
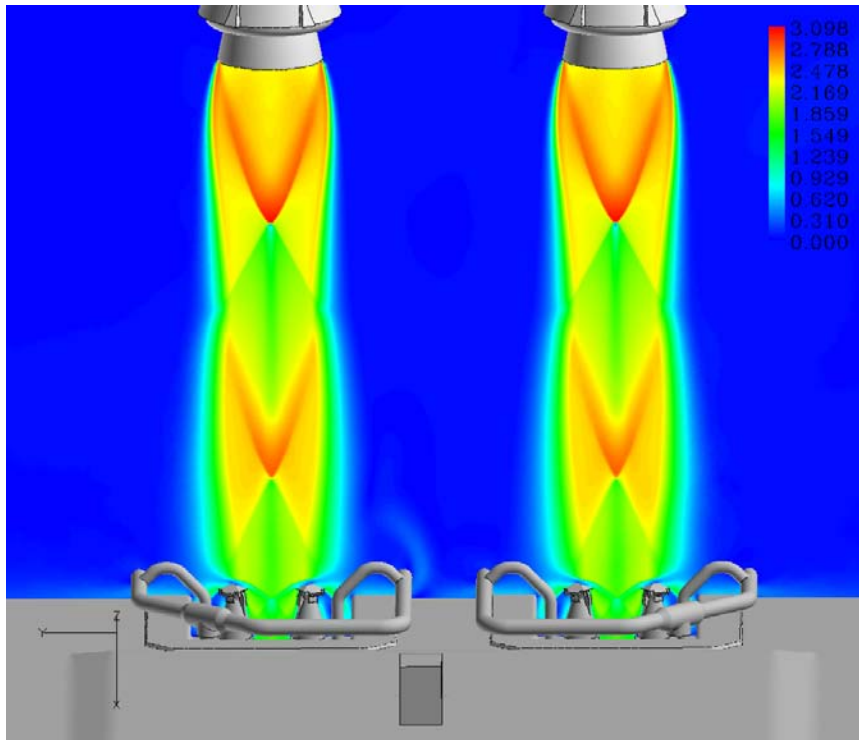


Wind 34 kts from 270 deg

- 3 SSME and 2 SRB Plume Flow Modeled With Variable Gamma Plume Gas Effects
- Steady-State, Vehicle Position at $T_0 + 3.0$ sec
- Plume Iso-surfaces at $M=1.0$ Show Plume Flow In Trench And Interaction With MLP



- Mach Number at ZT=400" (Plane Through center of ET and SRBs)
Strong Plume Impingement Interaction with Blast Deflectors of North SRB Haunches





Adding Plume Unsteadiness And Vehicle Motion Effects



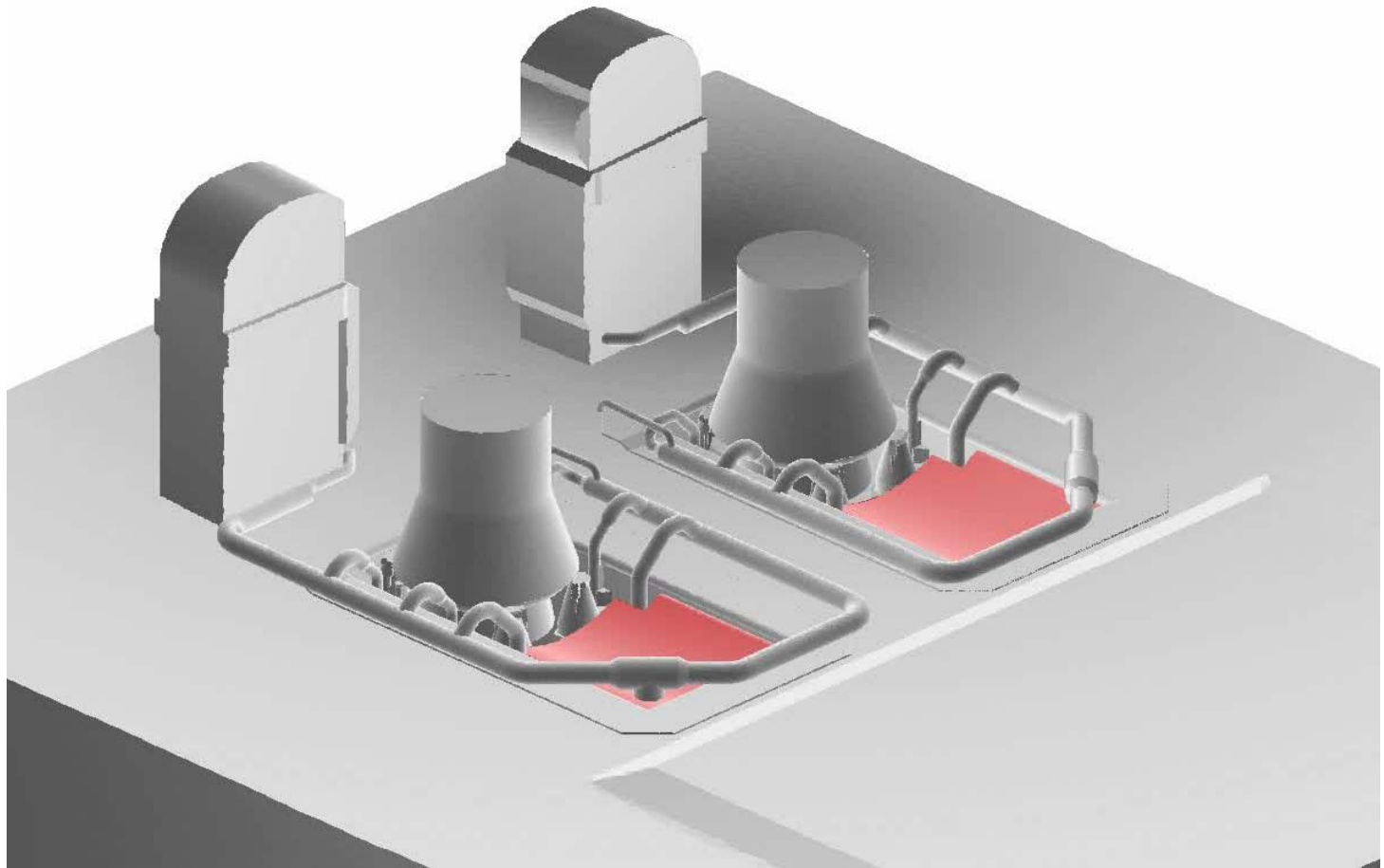
- Most of Shuttle Lift-off Debris Transport Analysis Was Performed With Quasi-steady State Simulations (Vehicle Held Fixed In Space)
- LODTA Team Succeeded in Resolving Most Wind Driven And Plume Driven Debris Threat Analyses With This Level Of Fidelity
- A Number Of Debris Events And Several Mishaps Could Only Be Explained When Considering Unsteady Plume Flow Features And/Or Vehicle Motion Effects
- Utilizing Recently Matured Overset Grid Moving Vehicle Simulation Capabilities To Add Flow Effects Resulting From Vehicle Motion
- Also Including Unsteady Hybrid RANS/LES Plume Turbulence Modeling To Capture Large Unsteady Plume Features
- Following Animations Show Current Level Of Simulation Capabilities For Predicting Plume Flow Interaction With Launch Pad
- Simulations Are Representative Of Current State of Support Activities of MSFC Fluid Dynamics Branch In Defining Liftoff Flow Field Environments For Launch Vehicles



Space Shuttle Moving Body Simulation



- Moving body simulation of two SRB plumes moving on the Shuttle liftoff trajectory
- Isosurface of 2% Plume Gas mass fraction
- Upward plume splash in SRB Holes at early times
- Upward moving flow due to plume merging on top of MLP Deck at later times



massFraction = 25

Embedded Animation

0.0725000



Space Shuttle Moving Body Simulation



- Moving body simulation of two SRB plumes moving on the Shuttle liftoff trajectory
- Static Pressure on Plume Deflector in Launch Pad Flame Trench
- Motor start-up and Ignition over-pressure transients passing through at early time
- Highly unsteady localized high impact pressure spots
- Large unsteadiness of pressure zones as plume interacts with MLP structure



./output/pg_sca.25_launch

Embedded Animation

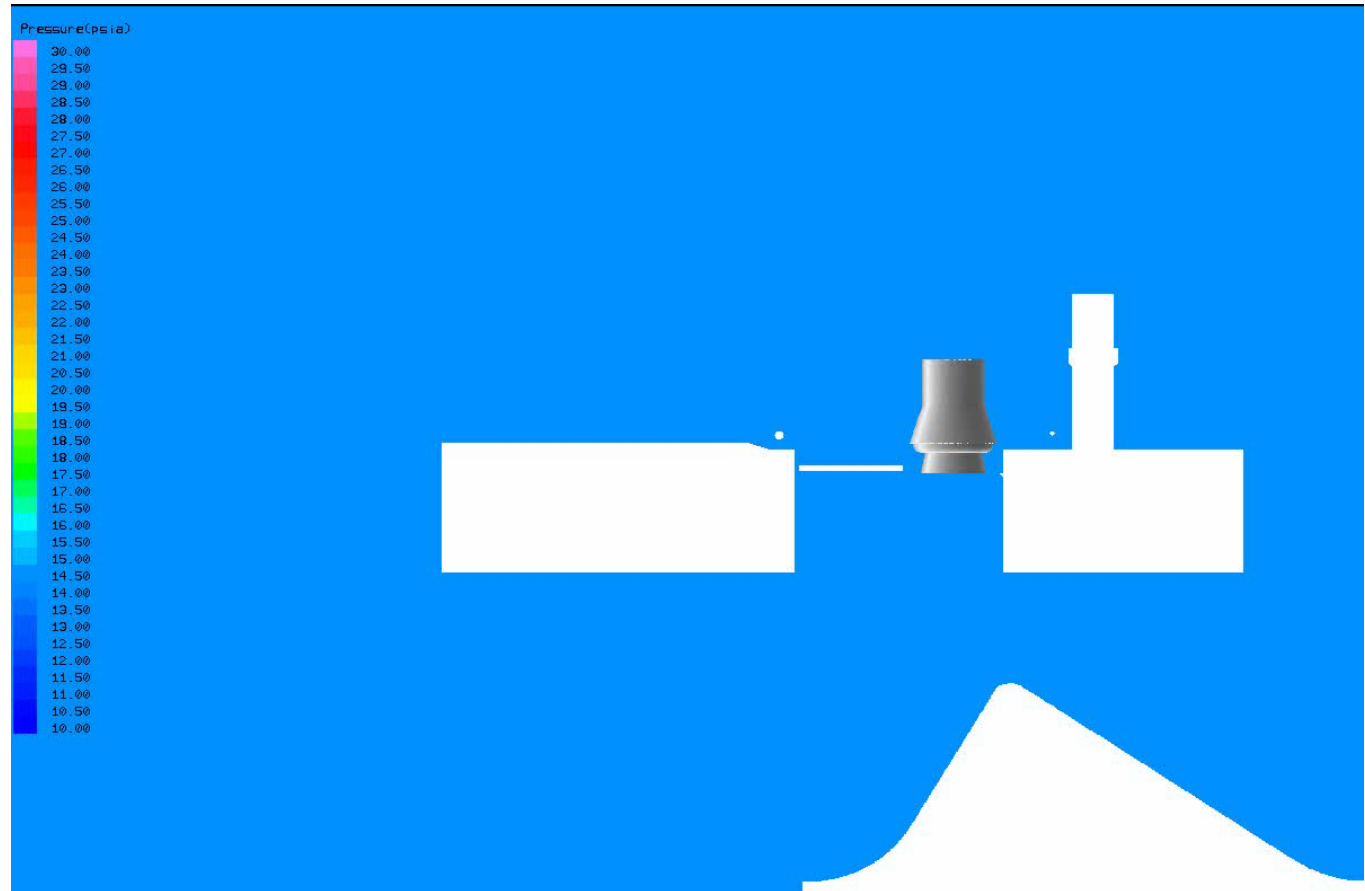
0.0725000



Space Shuttle Moving Body Simulation



- Moving body simulation of two SRB plumes moving on the Shuttle liftoff trajectory
- Static Pressure in plane through center of SRB
- Highly unsteady localized high impact pressure spots
- Increased unsteadiness of pressure zones as plume interacts with SRB haunch structures



./output/pg_sca.25_launch

0.0725000

Embedded Animation



Conclusions



- Plume Driven Debris Transport Is Most Dangerous Threat to Launch Vehicles During Liftoff Phase
- Shuttle Liftoff CFD Model has been Constructed with Significant Geometrical Detail In all Regions of Plume Interaction with Launch Pad Structures
- Majority of Shuttle Liftoff Debris Transport Analysis Cases have been Successfully resolved through Quasi-Steady Plume Flow Simulations
- Steady State Only Simulations Miss Number of Short-Lived, Critical Flow Events And Features
- Inclusion of Moving Vehicle, Unsteady Flow, And Plume Large Eddy Effects Enables Capturing Unsteady Flow Physics



Appendix



Agenda

Second Workshop on Lunar and Martian Plume Effects and Mitigation

NASA KSC

January 20-21, 2011

Day 1 (Jan 20)

1. Context (08:30 to 10:10)
 1. Phil Metzger: The Role of Plume Management in Space Exploration
 2. Anita Sengupta: Mars EDL plume impingement (effects on descent, radar, and rovers)
 3. Karl Edquist: Development of Supersonic Retropropulsion for Mars Exploration
 4. Sandy Wagner: Debrief on the Lunar Regolith Behavior Workshop
 5. Wayne Finger: Launch and Landing Infrastructure on the Moon
2. Break (10:10 to 10:25)
3. Phenomenology (10:25 to 12:00)
 1. Phil Metzger: Five regimes in rocket exhaust cratering
 2. John Lane: Apollo video/photo analysis of exhaust plume effects
 3. Phil Metzger: Phenomenology of erosion of a complex regolith
 4. Ryan Clegg: Damage to spacecraft hardware due to impact of soil ejecta
 5. Paul Hintze: Analysis of Surveyor III damage from impact of Apollo 12 soil ejecta
4. Lunch (12:00 to 13:00)
5. Experiments (Start during Lunch, 12:30 to 13:40)
 1. Phil Metzger: Scaling of Erosion Rate
 2. Casey LaMarche: Cratering of Particle Beds by a Subsonic Turbulent Jet
 3. Manish Mehta: Diffused Gas Explosive cratering experiments for PHX
6. Mitigation, Part I (13:40 to 15:20)
 1. Van Townsend: Rover platforms and attachments to grade and compact landing site and build berms
 2. Paul van Susante: Lunar landing pad construction technologies mounted on rovers
 3. Paul Hintze: Lunar/Martian soil Stabilization technologies including tests on Mauna Kea
 4. Jan-Michael Gosau: Polymer-based soil stabilization technology
 5. Holly Shulman: Microwave sintering for soil stabilization
7. Break (15:20 to 15:40)
8. Mitigation, Part II (15:40 to 17:00)
 1. Luke Roberson: Technology for lunar mats and inflatable fences
 2. John Lane: Analysis of effectiveness of lunar fences and berms (berms are NOT effective in vacuum; they simply scatter most of the debris)
 3. Phil Metzger or Paul van Susante: cold gas tests to evaluate landing pad technology effectiveness (including gravel beds)
 4. Van Townsend: how to test landing pad materials at a VTVL testbed (recent Masten tests)



Appendix (Cont.)



Agenda

Second Workshop on Lunar and Martian Plume Effects and Mitigation

NASA KSC

January 20-21, 2011

Day 2 (Jan 21)

9. Modeling, Part 1 (08:30 to 09:50)
 1. Bruce Vu: Launch-Induced Environment Modeling: from Combustion to Ablation
 2. Peter Liever: Modeling of Shuttle debris transport
 3. John Lane: Dust, soil and rock ballistics on the Moon
 4. Aaron Morris: U. Texas modeling of lunar plumes and soil ejecta
10. Break (09:50 to 10:00)
11. Modeling, Part 2 (10:00 to 12:00)
 1. Brian Moore (U.C.F.): Modeling of diffused gas causing soil failure
 2. Christine Hrenya (C.U.): Role of Collisions in the Erosion of Lunar Regolith
 3. Casey LaMarche (U.F.): Two-Fluid Modeling of a Subsonic Turbulent Jet Impinging on a Particle Bed
 4. Steven Diaz: F.I.T. modeling TBD
 5. Chunpei Cai: Zona Technologies progress in integrated modeling of soil and rarefied gas flow
 6. Peter Liever: CFD Research Corp. progress in integrated modeling of soil and rarefied gas flow
12. Lunch on your own (12:00 to 13:00)
13. Discussion (13:00 to 15:00)
 1. What are the gaps in our understanding of the physics and phenomenology?
 2. What are the gaps in the modeling?
 3. What technology gaps exist for mitigation?
 4. Roadmap future research and technology development